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Optimal design of metro automatic train operation speed profiles for reducing energy consumption

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Abstract: Trains equipped with automatic train operation (ATO) systems are operated between stations according to the speed commands they receive from balises. These commands define a particular speed profile and running time, with associated energy usage (consumption). The design of speed profiles usually takes into account running times and comfort criteria, but not energy consumption criteria. In this article, a computer-aided procedure for the selection of optimal speed profiles, including energy consumption, which does not have an effect on running times, is presented. To this end, the equations and algorithms that define the train motion and ATO control have been modelled and implemented in a very detailed simulator. This simulator includes four independent modules (ATO, motor, train dynamics, and energy consumption), an automatic generator of every possible profile and a graphical assistant for the selection of speed commands in accordance with decision theory techniques. The results have been compared with measured data in order to adjust and validate the simulator. The implementation of this new procedure in the Madrid underground has led to a 13 per cent of energy saving. As a result, the decision has been taken to redesign all the ATO speed profiles on this underground.

Keywords: energy consumption, speed commands design, train simulation, energy efficient driving, automatic train operation, metro, eco-driving

1 INTRODUCTION

Trains equipped with automatic train operation systems (ATO) receive from balises the parameters needed to be driven between each two stations. These parameters correspond to one of a pre-programmed set of alternative ATO speed profiles per inter-station distance. As a result, traffic control system performance and total energy consumption strongly depend on the off-line design of the ATO speed profiles.

The ATO speed profile is selected online by the control system according to the required running time [1]. When a train must be held up, from the user's point of view a longer running time is preferred rather than a longer station waiting time. In addition, this control

strategy involves energy savings because slower speed profiles result in fewer traction periods and therefore less consumption. However, these ATO speed profiles have usually been designed according to running time and comfort criteria, but not to energy consumption criteria.

In order to find speed profiles that optimize energy use, mathematical models have been applied, principally optimal control techniques. In reference [2], the optimal speed profile is calculated with the maximum principle. The algorithm finds the minimum consumption speed profile and can be used on board. However, in the case of ATO systems, a continuous control of the driving is not possible because of the finite number of configuration parameters.

The study in reference [3] considers the problem of the optimal driving strategy based on a generalized equation of motion that can be used in discrete and continuous control. For continuous control, the technique used is similar to that previously mentioned [2]. It makes use of the Pontryagin theorem. For discrete control, Kuhn–Tacker equations are used. The result is

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a theoretical approach to the search for the switching points of the driving mode.

The authors of reference [4], seeing the difficulties of resolving the optimal control problem with numerical techniques, developed a discrete dynamic programming algorithm. They use kinetic energy instead of speed and obtain an analytical solution in real time. In reference [5], Bellman's dynamic programming has also been used to optimize the running profile of a train. The authors transform the original problem into a multi-stage decision process accomplished by linearization and time-uniform discretization.

These approaches include simplifications in their track, trains, and driving models. This means that they are not appropriate for the optimal design of metro ATO speed profiles given the short inter-stations in metropolitan lines and the differences of a few seconds between the ATO profiles to be designed. Therefore, accurate models are needed.

The difficulty involved in the analytical resolution of the problem means that approaches based on simulation are an alternative. They do not require simplifications and enable an accurate calculation of running times and energy consumption, as [6] manual driving modelling for freight trains. A number of optimization techniques have been used in combination with simulation. In reference [7], genetic algorithms (GA) are used to find the optimal location of coasting points by trading off reductions in energy against increases in running time. A fitness function with variable weightings was used to identify optimal train trajectories. The influence of the weightings is clear. GA have also been used in reference [8] and applied to a real case on Seoul City's MRT (Mass Rapid Transit) system. The solutions are compared with P. Howlett's optimization method.

Artificial neural networks have also been used. In reference [9], it is proposed that they are used to obtain the optimal coasting speed. The objective function is formulated by considering the cost of energy consumption and the cost of passenger travelling time. Chang and Xu [10] include Pareto efficiency in differential evolution to find a trade-off between punctuality, consumption, and comfort.

GA have also been used for online optimization. In reference [11], the authors propose the optimization of a coast control based on the evaluation of the punctuality, riding comfort, and energy consumption that can be integrated within ATO systems. In reference [12], GA are combined with artificial neural networks to optimize coasting points for manual driving. Once again, the results depend on the weightings of running times and energy consumption in the fitness function.

It is also possible to find models of the train forward motion. In reference [13], train motion equations are solved with a modular simulator without including any control system. In reference [14], two mathematical models and algorithms that are used in a simulator for

generating train speed profiles are developed without optimizing the driving.

However, these models cannot be implemented to solve the authors' problem. The features of the ATO system considered make necessary a different approach which rather than using a continuous control curve, optimize the discrete configuration parameters of the equipment.

This article is focused on the computer-aided design of a set of ATO speed commands between two metro stations. The project is a real implementation based on the research in reference [15], which described the savings which could be expected. The variables taken into account are the configuration data of the ATO system, four parameters in the case study: coasting, remotoring, speed holding value, and braking deceleration rate. The considered ATO system provides only certain discrete values for each parameter, resulting in a solution space of 156 alternative speed profiles per inter-station, which makes possible the exhaustive and accurate simulation of all the feasible ATO speed profiles. Decision theory techniques can be directly applied to select a set of solutions per inter-station (four in the case study), including operational, comfort, and energy consumption criteria. Thus, the obtained driving solutions are fully adjusted to the real features and capabilities of the ATO equipment in service.

A software tool for computer-aided design of ATO speed profiles was developed to support the design procedure defined. The following sections will describe the models, the simulator, the proposed design procedure, and the results of its implementation on line 3 of the Madrid underground.

2 THE MODELS

When designing an energy-efficient driving pattern, the decision variables are running time and energy consumption while the comfort criteria must be met. Simulation results of these variables must be precise in order to make a proper decision. The adjustment of simulation results depends on the accurate simulation of the complete journey of a train between two stations. To achieve this accuracy, the simulation model has been modularized. Each module represents the different subsystems of a real train (Fig. 1). Consequently, it is possible to validate each module separately, identify and isolate errors, and adjust each module in order to obtain sufficient precision. This design also allows the swapping of modules to simulate a new train or ATO equipment.

2.1 ATO model

The ATO model represents the control logic of the driving. Based on the speed and position of the train, the

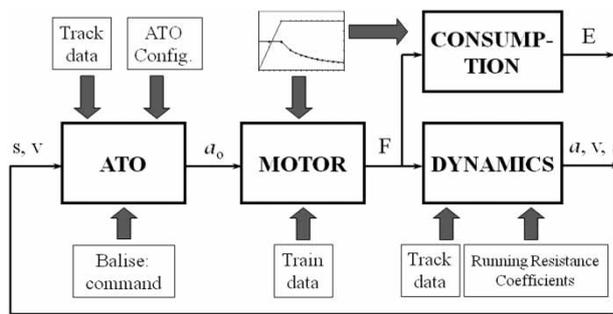


Fig. 1 Block diagram of the modularized model simulator

ATO computes the traction set value to achieve the running time needed, but always bearing in mind the maximum and minimum speeds. Information about the line topography and the commands of the balises is needed. To obtain accurate results, the equipment cycles and hysteresis were included in the calculations.

The ATO signal (a_o in Fig. 1) is bounded, and is calculated in equation (1) as a speed increment to achieve the target velocity, and corrected with the gradient. This calculation functions as a proportional controller, where k assures that the target speed is achieved in a certain period of time

$$a_o = k(V_{\text{target}} - V) + a_g \quad (1)$$

2.1.1 Braking to target speed

Information about the line, with the speed restrictions at each kilometre point, is stored in the memory of the ATO equipment. Thus, before reaching a speed restriction, the target deceleration of the ATO system will allow the train to adjust to the restriction in a safe and comfortable way.

The start of braking due to a speed restriction is evaluated for every simulation step in which the control algorithm of the simulated ATO is executed. This algorithm assumes four periods with different accelerations which depend on the speed and coasting before braking.

Once the initial and final points of braking and their target speeds are known, it is possible to calculate a theoretical braking curve. Then, deceleration is calculated using this curve, which is modified by means of the increment of speed with respect to this curve and the gradient (equation (2)). The performance is again similar to a proportional controller but in this case, $k(V)$ depends on the speed

$$a_o = k(V)(V_{\text{ref}} - V) - a_{\text{ref}} + a_g \quad (2)$$

2.1.2 Braking to stop

Once again, the ATO system tries to detect the starting point of the braking to stop. This point must be located to ensure that the train comes to a complete halt, with

the maximum values of deceleration and with smooth transitions from the previous state to braking.

Using the command deceleration received from the balise, the stopping curve is saved in memory from the beginning of the simulation. In this case, the gradient is only taken into account if it is negative and if the sum with the deceleration command is greater than the braking limitation.

In each cycle of the simulated equipment, the model calculates distance which results from travelling a short period of time with maximum acceleration. At that point, if the result of equation (3) is 0 or negative, it is the starting point for braking to stop

$$k(V)(V_{\text{ref}} - V) - a_{\text{ref}} \quad (3)$$

Once the beginning of braking is detected, the deceleration of braking to stop is also calculated as an increment with respect to a theoretical curve between the initial and the stopping point (equation (4)). This will be the target deceleration for the train

$$a_o = k'(V)(V_{\text{ref}} - V) - a_{\text{ref}} + a_g \quad (4)$$

2.2 Motor model

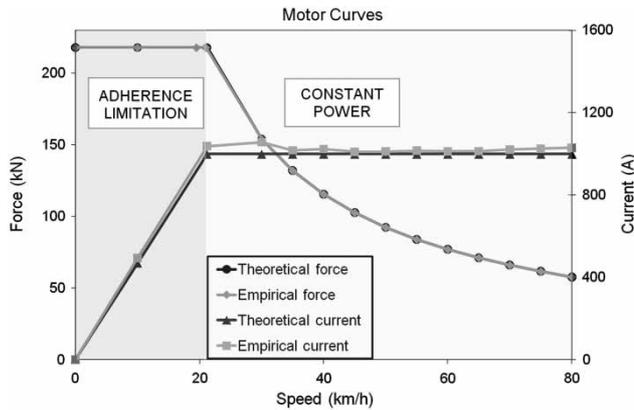
With this model, both the traction effort to achieve the traction set value calculated in the ATO model and the current are found. The modelled train is made up of four trailers and four tractive cars with four induction motors per each one. The electric traction system is three-phased with IGBT (insulated gate bipolar transistor) asynchronous drives and is microprocessor controlled. The model needs the mass of the train plus the rotational inertial effect and the traction effort available depending on the speed. Motor features are shown in Table 1.

Motor curves (force and current) are characterized by two areas. In the first one, motor force depends on the load the train is carrying and current depends also on the speed as is shown in Fig. 2. Consequently, the curves in the function of mass should be provided by the manufacturer, which is usually possible. However, in the second area where power and current are constant, the values of the traction force are under the load limitation and the limit is the power. Now curves (force and current) depend on the ratio between required force and maximum traction force as well as the speed in the case of force. As a result, in this area there will be another set of curves for different ratios and it would be possible to interpolate. The theoretical curves of traction effort and current have been adjusted based on real measurements as shown in Fig. 2.

The set value result of the ATO model is interpreted by the motor as the ratio between required force and maximum traction force corresponding to the speed at each simulation step. The maximum traction force, corresponding to the maximum ATO value, is shown

Table 1 Train parameters

Running resistance (daN/t)			Length of train	Tare weight	Rotational inertial effect	Maximum passenger load	Load for simulations	Voltage	ATO cycle	Motor cycle	Braking cycle
A	B (km/h)	C (km/h) ²	(m)	(t)	(% tare weight)	(t)	(% maximum load)	V	(number of 50 ms cycles)		
1.881	0.02	0.00042	89.16	159.697	8.19%	78	30%	1500	5	5	10

**Fig. 2** Experimental and theoretical motor curves

in Fig. 2, where the train load imposes a maximum limitation. When the speed of the train corresponds to the first area of the curves, the force is calculated by equation (5); otherwise, it is calculated by equation (6). To improve the results, even the motor time lag with respect to the ATO system has been included

$$F = \frac{M}{M_{eq,max}} \cdot a_o \cdot F_{max} \quad (5)$$

$$F = a_o \cdot F_{max} \quad (6)$$

In order to assure the comfort of passengers, control equipment in the motors prevents an abrupt change in force in transitions like traction braking or braking traction. Therefore, a jerk limitation ($da/dt|_{lim}$) has been included in the motor model, following equation (7)

$$\frac{1}{M_{eq}} \frac{dF}{dt} > \frac{da}{dt}|_{lim} \Rightarrow F_2 - F_1 = M_{eq} \cdot j(t_2 - t_1) \quad (7)$$

2.3 Dynamics model

Finally, the new acceleration, speed, and position of the train must be calculated. For this purpose, the resistance to train movement is needed.

It is well known that mechanical rolling resistance and aerodynamic drag is modelled as in equation (8). Since the line is only underground operated, the C term remains constant. This value as well as other train parameters is shown in Table 1

$$F_{rr} = A + BV + CV^2 \quad (8)$$

To take into account the gradient profile, a list with the initial and final points of downhill and uphill sections, their values, and the slope transition curves is needed. Lateral curves are treated as equivalent slopes (equation (9)) added to the actual ones. At each simulation step, an average of the gradient where the train is situated is calculated (equation (10))

$$p_i = \frac{K}{R} \quad (9)$$

$$p_m = \frac{\sum_{i=0}^L l_i \cdot p_i}{L} \quad (10)$$

Train acceleration is the result of equation (11). Then, speed and position are calculated with equations of uniformly accelerated linear motion assuming constant acceleration at each short step time. The step time considered is 50 ms, because it is a least common multiple of all the cycles involved in calculations and it provides a high precision in calculations

$$a = \frac{\sum(F - F_g - F_{rr})}{M_{eq}} \quad (11)$$

2.4 Consumption model

The energy consumption of motors is calculated as the electrical power consumed at each time step increase (equation (14)) when motoring. Since the ATO speed profiles design will be carried out off-line and executed on different traffic scenarios, the voltage was assumed to have the nominal value of 1500V. The current was obtained in the motor module by selecting the curve corresponding to the ratio between the required and the maximum traction force when known. If the current is negative it is considered as regenerative energy

$$E = I \cdot U \cdot \Delta t \quad (12)$$

2.4.1 Motor efficiency regarding the ratio between the required and the maximum traction force

The set of curves depending on the ratio between the required and the maximum force is not usually supplied. On these occasions, the current curve corresponding to the maximum force is the only one known. The current consumed could be calculated from this maximum curve and the cited ratio, assuming a constant efficiency, but this assumption would not be

realistic. Therefore, a model including the variation of the efficiency in this ratio is needed. Starting from this variation, a penalty factor pf which corrects the consumption was modelled (equation (13))

$$E = I_{\max} \cdot \frac{F(V)}{F_{\max}(V)} \cdot U \cdot \Delta t \cdot \frac{1}{pf} \quad (13)$$

3 ATO SPEED PROFILES DESIGN

At this stage, the aim was to design a set of alternative speed command profiles. The first (number 0) is characterized by the minimum running time (flat-out), that is to say, applying maximum available acceleration, speed, and deceleration. The remaining profiles are slower but correspond to lower energy consumption. The maximum time gap between the fastest and the slowest is bounded as an operational criterion.

As has been mentioned, every speed profile is defined by four parameters. Consequently, coasting points are defined by speed, not by distance. This case highlights the importance of accurate and realistic simulations. An error of a few metres in a coasting point could make a train to coast in an inappropriate place like the ending of a very steep slope, which is uncomfortable. In consequence, an uncomfortable profile could be wrongly accepted by the simulator.

In the ATO system being considered, a command of coasting makes speed holding in the same speed profile impossible. As a result, the solution space is formed by speed profiles with speed-holding command or with coasting-remotoring command. A profile with a coasting command is usually considered more efficient. However, as comfort restrictions are involved, solutions with speed-holding command could be selected instead.

Energy consumption is considered as a cost driver and running times as a constraint. Therefore, it is necessary to find a trade-off between costs and times. Decision theory techniques were used to solve this multi-criteria problem. A consumption-time graph is presented in order to study the optimal solutions which are denoted by the Pareto curve as shown in Fig. 3.

3.1 Domination criterion

In accordance with the domination criterion, solutions with the desired time that lie in the Pareto curve are chosen. An example is given in Fig. 3, where one speed command profile is dominated by two others with almost the same running time.

3.2 Consumption sensitivity criterion

As the running time increases, the energy consumption of the Pareto curve decreases. That is to say,

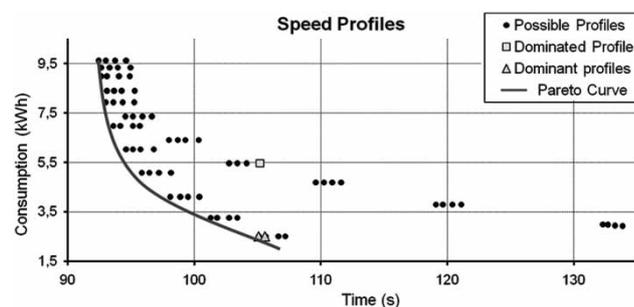


Fig. 3 Time-consumption graph, Pareto curve and illustration of the domination criterion

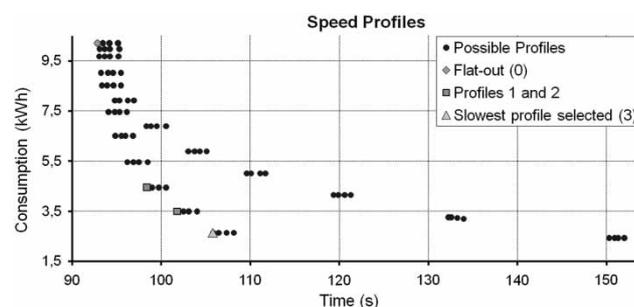


Fig. 4 Consumption sensitivity and temporal uniform distribution criterion

solutions near the flat-out are associated with high-energy costs per second. These costs decrease, reaching almost 0 at the end of the curve, where the speed profile number 3 (the slowest) can be located (Fig. 4).

3.3 Temporal uniform distribution criterion

The fastest and the slowest speed commands are selected according to the previous criteria. Two more speed commands (numbers 1 and 2) must be uniformly distributed as shown in Fig. 4 in order to achieve a smooth functioning of the traffic control system.

4 APPLICATION CASE STUDY

4.1 Parameter fixing and validation of the simulator

The models described were implemented in several simulation modules. Some interfaces for the input data were also included. The tool makes possible the simulation not only of a specific speed profile, but also of all the possible profiles between stations automatically. These speed profiles are obtained by computing all feasible combinations of the ATO configuration parameters. Then, a time-consumption graph is represented with the simulated speed profiles, and the previously described design procedure is applied to select the set of four profiles per inter-station.

The parameters fixing and validation of the simulator to fit the models and adjust the tool is an important aim to get reliable result since the final goal is the implementation of the speed profiles design and the operative restrictions of regulation allow only few seconds of difference between profiles. First, measurements were taken one day to fit the models and adjust the simulator. After that, the design was carried out and implemented. Then, new measurements were taken during 2 days to calculate savings. Measurements were taken on board. A laptop was connected to the traction control system in order to record speed, acceleration, traction force, pneumatic brake, voltage, current, load of passengers, ATO commands, and ATP signal at each 64 ms.

To fix the simulation parameters and validate the simulator, the error of each module had to be evaluated, comparing simulated outputs with registered data. The recorded input variables are inputted into the model, then the calculation of the corresponding algorithm is carried out and the resulting output is compared with the recorded output.

For ATO model the comparison between the real ATO set value and the modelled one is shown in Fig. 5

if it is not braking. In that case, Table 2 compares some of the detection points for braking to target speed taken from measurements those obtained from simulation, once the parameters of the model were fixed. The expected average difference is 2.0 per cent with respect to the inter-station length travelled and 0.8 per cent with respect to the complete inter-station distance. In addition, a complete simulation is shown in Fig. 6 and compared with real data. Similarly, some of the simulated detection and starting braking points to stop are shown in Table 3. An average difference of 0.8 per cent was measured with a maximum of 4.5 per cent.

Recorded data were also used to verify the ATO output in braking mode (equation (2)). The speed reference was calculated with the position and the speed of the starting point of braking to target speed, its value, and its position. Then, the ATO set value was obtained, with the equipment cycle and a time lag between speed and ATO also being taken into account. Results are shown in Fig. 5 in comparison with real data.

To verify the reliability of the motor model, the measured ATO output has been inputted in equations (5)

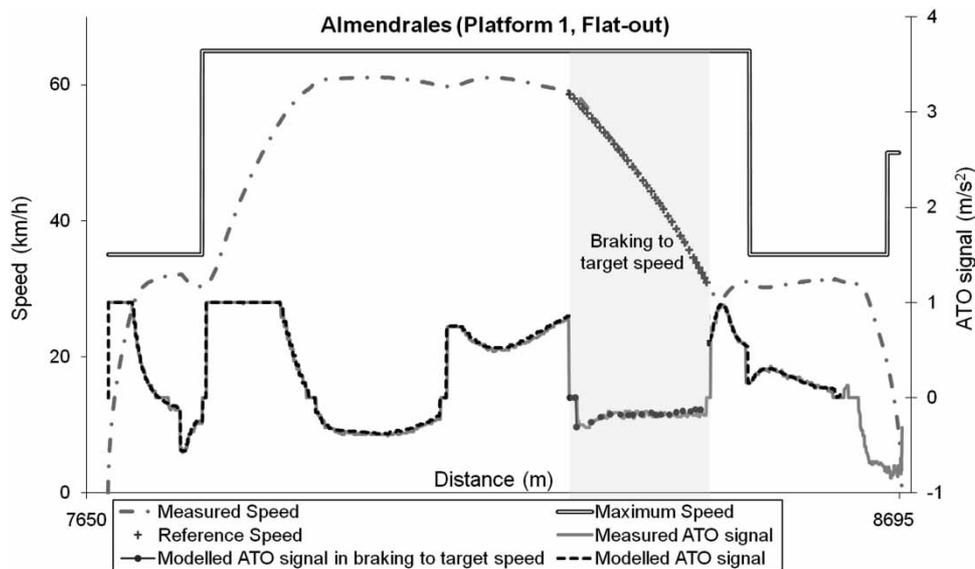


Fig. 5 Comparison between real and modelled ATO signal

Table 2 Comparison between real and simulated detection points in braking to target speed in some inter-stations

Station	Measurements Starting point for braking to target speed (m)	Simulations	Error		
			Difference (m)	With respect to travelled distance (%)	With respect to inter-station distance (%)
AR2	809.61	809.53	0.08	0.07	0.02
VR2	1263.30	1261.83	1.47	1.00	0.30
PE2	1985.58	1983.34	2.24	0.58	0.39
S2	2939.65	2933.52	6.13	1.92	0.63
EM2	4553.20	4550.86	2.34	0.47	0.30
DL2	5616.83	5611.16	5.67	2.10	0.73

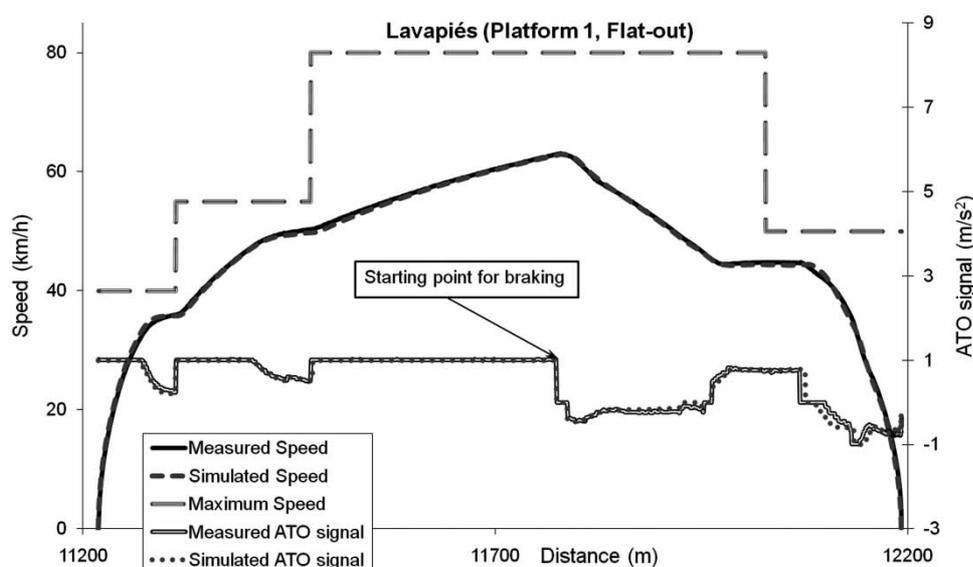


Fig. 6 Speed and ATO measured and simulated. Start point for braking marked

Table 3 Comparison between real and simulated detection and starting points in braking to stop in some inter-stations

Station	Simulations	Measurements	Error	
	Kp (m)	Kp (m)	(m)	(%)
CL1	5901.22	5900.08	1.14	0.10
L1	9359.16	9364.48	-5.32	-0.68
C1	13 079.11	13 081.02	-1.90	-0.33
PE1	13 513.16	13 519.37	-6.21	-1.45
AR2	1027.21	1026.56	0.65	0.14
VR2	1466.76	1467.57	-0.81	-0.19

and (6) as well as the curve of maximum force. The motor force is obtained and it is compared with the measured one in Fig. 7. The model considers the jerk limitation in force transitions as shown in Fig. 8. In addition, Fig. 8 shows both the simulated profile and the recorded one with the coasting-remotoring command.

Differences between a simulation with slope transition curves and a train with a distributed mass instead of sharp slope vertices and a point mass train are evident as shown in Fig. 9. Although the difference between them is appreciable, these details are frequently simplified in the literature. As previously justified, the required level of accuracy of the application case makes it necessary to model the distributed mass of the train with a variable and continuous gradient along it.

Thanks to the measurements it has been also possible to fit the models of energy consumption and the associated efficiency model to get reliable results. The variation of the efficiency with the ratio between the required and the maximum traction force used as a penalty factor which corrects the consumption

responds to equation (14)

$$\begin{aligned}
 \text{pf} &= 1 \quad 95\% \leq F/F_{\max} < 100\% \\
 \text{pf} &= 0.6620 + 0.3558\%F \quad 50\% \leq F/F_{\max} < 95\% \\
 \text{pf} &= 0.5714 + 0.537\%F \quad F/F_{\max} < 50\%
 \end{aligned}
 \tag{14}$$

Finally, after the parameters were fixed, the model was validated. The results of the calculation of energy consumption and real values are shown in Table 4 for several inter-stations. The average difference between them is 1.5 per cent. A comparison of complete simulations and measured data was also carried out and is shown in Table 5, consumption and running times are compared. An average difference of 4.2 per cent in energy usage and 1.0 per cent in running times is obtained.

In order to compare the results with the measured real data which do not include them, auxiliary and comfort system consumption were not taken into account in the calculations.

4.2 Comfort restrictions

To ensure the successful implementation of suitable speed profiles from the passengers' point of view, it was necessary to include the comfort and operational criteria of the Madrid underground in the selection of the optimal speed profiles. To this end, a speed command profile is ruled out by the simulator if it does not pass a constraint. Comfort and operational restrictions were defined in collaboration with Metro de Madrid: minimum speed throughout the journey (20 km/h), maximum number of remotoring (three), maximum slope where coasting is possible (25 mm/m), and a list of minimum speed limits along curves.

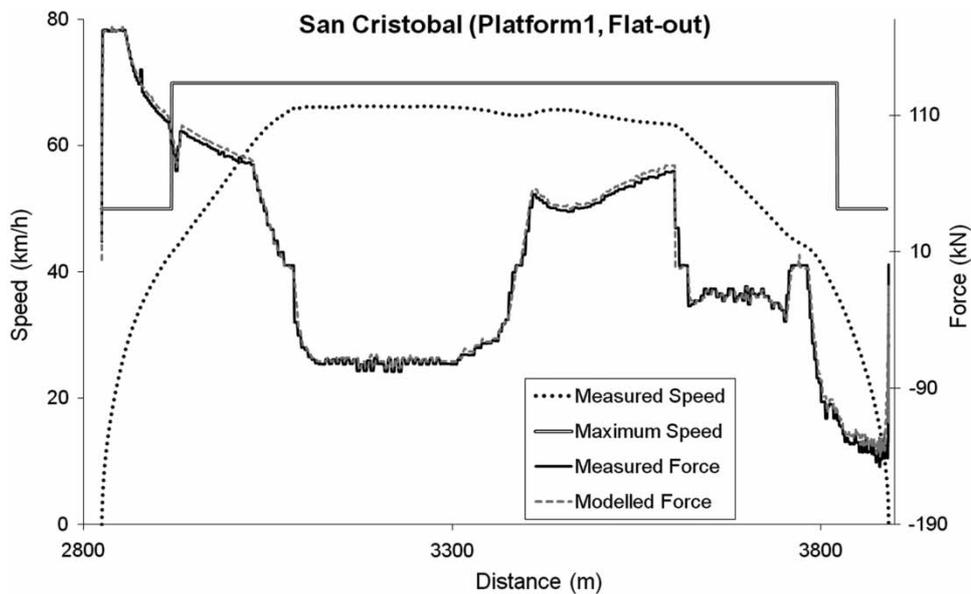


Fig. 7 Measured force in comparison with the modelled one

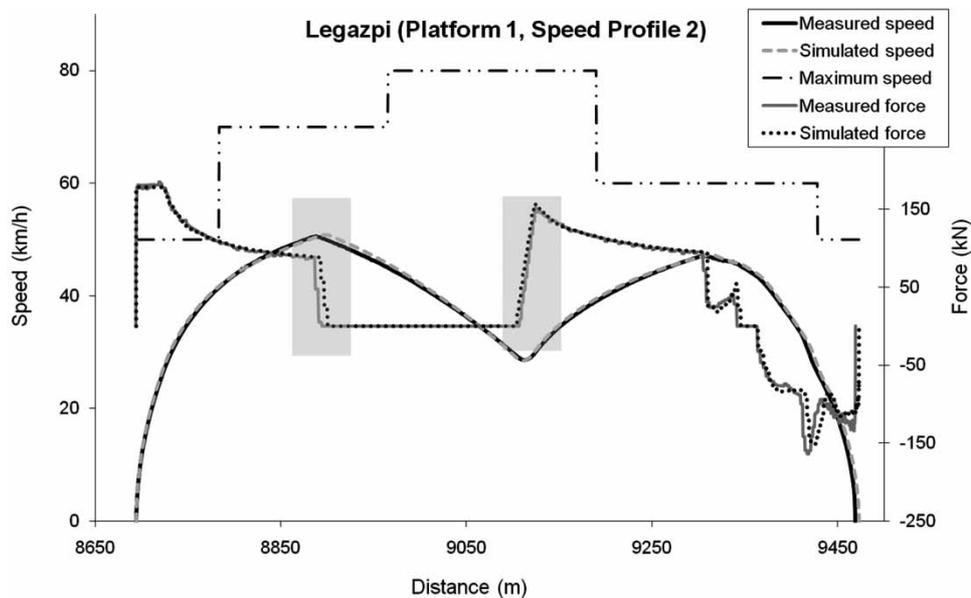


Fig. 8 Comparison of the simulation of coasting-remotoring with measurements. Simulation of motor jerk limitation marked

As a result, all the possible speed profiles are comfortable in only four inter-stations. There are 18 inter-stations where more than 50 per cent of speed profiles observe all the restrictions, ten inter-stations where more than 50 per cent of speed profiles do not fulfil some comfort or operative restrictions (1213 profiles of the total 1716), and two inter-stations in which only the flat-out is possible.

4.3 Speed profiles design of Metro de Madrid line 3

After calibration, the simulator was used in the design of a set of four alternative speed profiles per

inter-station for line 3 of the Madrid underground. It is a line with 17 stations per direction with an average length of 810 m and uneven track with slopes up to 50 mm/m.

From the time-consumption graph, the flat-out (0) and three other speed profiles (1, 2, and 3) are selected following the domination, sensitivity, and temporal uniform distribution criteria with a maximum time gap bounded to 20 s between profiles 0 and 3. An example is given in Fig. 10.

The new speed profiles designed as part of this project were implemented in the ATO equipment and are currently being used. Measurements were

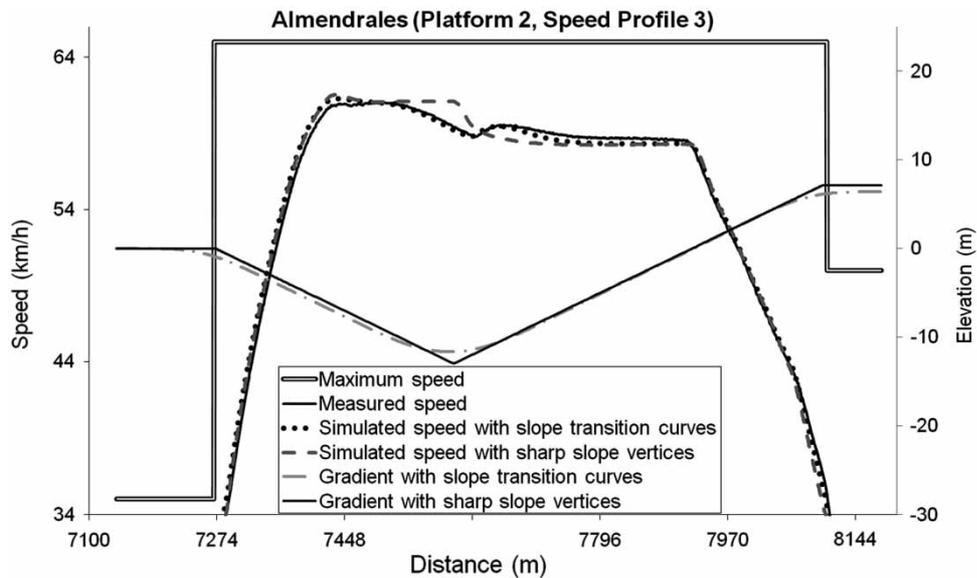


Fig. 9 Simulation with a gradient with sharp slope vertices and a point mass train in contrast with a gradient with slope transition curves and a train with a distributed mass

Table 4 Comparison of the results of the model of energy consumption with measurements in some inter-stations

Stations	Measurements		Model		Error	
	Distance (m)	Running time (s)	E (kWh)	E (kWh)	(kWh)	(%)
M2	402.70	52.47	9.94	10.01	0.07	0.71
AR2	474.14	56.18	2.65	2.71	0.06	2.35
VR2	430.76	53.50	3.16	3.24	0.08	2.39
PE2	572.25	64.63	15.38	15.40	0.01	0.10
S2	974.85	92.08	3.51	3.49	-0.02	-0.48
LV2	466.80	58.17	2.51	2.57	0.05	2.07
EM2	780.60	75.06	7.61	7.78	0.17	2.23

taken and the consumption of the old speed profiles compared with the current one. Table 6 shows the comparison for one inter-station journey; up to 38 per cent savings are achieved with the new speed profile number 1.

The running times of designed profiles number 1 are similar to the running times of the old profiles.

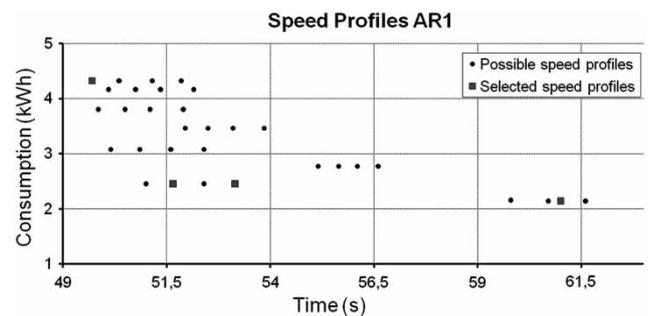


Fig. 10 Newly designed speed profiles in Argüelles platform 1

Table 5 Results of energy consumption and running times in complete simulations in comparison with measurements in some inter-stations

Stations	Measurements		Simulations		Error			
	Running time (s)	E (kWh)	Running time (s)	E (kWh)	Running time (s)	E (kWh)	Running time (%)	E (%)
PE2	65.78	15.68	66.55	15.92	0.77	0.24	1.17	1.51
C2	54.46	2.81	55.05	2.79	0.59	-0.02	1.09	-0.73
S2	93.81	2.86	94.70	2.85	0.89	0.00	0.95	-0.01
LV2	58.81	2.55	60.45	2.50	1.64	-0.06	2.79	-2.25
EM2	76.98	7.56	75.40	7.52	-1.58	-0.03	-2.05	-0.42
PF2	62.71	2.46	63.05	2.44	0.34	-0.02	0.54	-0.82

Table 6 Comparison of the energy consumption of the new and old speed profiles in Argüelles platform 1

	Speed profile no.	Deceleration (m/s ²)	Speed-holding (km/h)	Coasting (km/h)	Remotoring (km/h)	Running time (s)	Consumption (kWh)	Energy saving (%)
Old speed profiles	1	0.65	0	42	10	51.6	4.47	
	2	0.65	0	37	10	51.9	3.68	
	3	0.65	0	35	10	52.1	3.37	
New speed profiles	1	0.7	0	30	20	52.1	2.77	38.06
	2	0.6	0	30	20	53.7	2.77	24.85
	3	0.65	30	0	0	61.3	2.32	31.24

the flat-out and the slowest speed profile, which produce benefits in traffic regulation as well as energy consumption.

On average, with the redesign of all the stations in line 3, a 13 per cent saving is achieved with the new design.

4.4 Discussion

After the implementation of the first proposal for the line, it was necessary to redesign only eight speed profiles of 102, which means that it is not a trial and error procedure but a sound simulation approach.

Special importance has been attached to comfort in the application to Metro de Madrid line. Until now, designed profiles were implemented and subsequently tested in service to check comfort so many times as necessary until finding the comfortable ones. Thanks to the definition of concrete criteria and the simulator, this trial and error procedure is avoided ensuring the implementation of only comfortable and economical profiles. In fact, the simulation of the speed profiles in service before the redesign process, have shown that many of them were not comfortable according to the new defined criteria.

It is important bearing in mind that the described procedure responds to the necessity of carrying an off-line design that will be later executed in different traffic and load scenarios. Because of this, it is not possible to take into account voltage or load variation. To optimize the system it would be possible to design different sets of speed profiles for peak or off-peak hours if the traffic regulation system would allow it.

The efficiency model also produces important results. Since the efficiency decreases together with the ratio between the required and the maximum traction force, coasting–remotoring profiles will be preferable to speed holdings with low ratios of traction considering the trains of the application case.

5 CONCLUSIONS

The selection of the speed commands for programming the ATO on metropolitan trains has usually met comfort and operational criteria. With the new

design procedure described in this article, the energy consumption criterion is also taken into account.

For a proper design of ATO speed commands to be implemented, an accurate calculation of running times and energy consumption is necessary. Therefore, a detailed simulation model of all the train subsystems is needed, because mathematical models include simplifications. Comfort and operational restrictions must be considered in order to obtain feasible speed profiles.

In addition, current ATO equipment provides only a certain range of discrete configuration values. Thus, there are a finite and relatively short number of possible speed profiles that can be exhaustively simulated. Decision theory techniques can be applied to find solutions which provide a trade-off between running times and energy costs.

The models and the simulator developed have been presented in addition to the validations of the implemented speed profiles using real measurements.

From the design and implementation of the ATO speed commands on line 3 of the Madrid underground it is possible to conclude that an improvement of about 13 per cent in energy consumption is achieved without affecting running times. On high-frequency metro lines, the programmed speed profiles are repeated systematically many times, so the energy savings become significant. Consequently, the ATO speed profiles of all the lines of the Madrid underground are being redesigned with this computer-aided procedure.

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APPENDIX

Notation

a	acceleration (m/s^2)
a_g	acceleration of gradient (m/s^2)
a_o	ATO value (m/s^2)
a_{ref}	reference acceleration (m/s^2)
A	running resistance coefficient (daN/t)
B	running resistance coefficient (daN/t(km/h))
C	running resistance coefficient (daN/t(km/h)^2)
E	energy usage (kWh)
F	motor force (N)
F_g	gradient resistance (N)
F_{rr}	running resistance (N)
I	current (A)
j	Jerk limit (m/s^3)
K	constant
l	partial length of the train (m)
L	total length of the train (m)
M	train mass (kg)
M_{eq}	train mass plus the rotational inertial effect (kg)
p	slope (‰)
p_m	average of the slope (‰)
pf	penalty factor
R	radius curve (m)
t	time (s)
V	speed (m/s)
V_{ref}	reference speed (m/s)
V_{target}	target speed (m/s)